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Indoor Air Quality in Green Buildings: A Review and a Case Study

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ABSTRACT

The term "green building" is used to describe buildings that are designed, constructed, and operated, to have a minimum impact on the environment, both indoor and outdoor. Most discussions of green buildings refer to the importance of providing an acceptable, if not exceptional, indoor environment for the building occupants. However, these discussions of indoor environmental quality have not included many specific recommendations or criteria for building design, construction, or operation. Building projects described as green building demonstrations often make reference to indoor air quality, but these references are often general and qualitative. In addition, rating systems that have been developed to assess the "greenness" of a building are based largely on design features and are not particularly specific with respect to indoor air quality. This paper reviews the features of indoor air quality that are considered in green building discussions, demonstration projects, and rating systems. These green building features are discussed in terms of their completeness and specificity, and are compared to other guidance on building design, construction, and operation for good indoor air quality. A case study of indoor air quality performance in a green building is presented. This study includes a description of the indoor air quality features of the building and the results of a short-term indoor air quality evaluation of the building involving ventilation and contaminant concentration measurements.

INTRODUCTION

Green buildings have been described as being designed, constructed, operated, and maintained (and also demolished) to have a minimal negative impact on the environment, including the indoor environment of the building (Italiano 1994). In terms of the global environment, this can be achieved by employing some form of environmental life-cycle assessment of all components and resources involved with constructing, operating, and maintaining a building (Lippiatt and Norris 1995). In terms of the indoor environment, this means employing building materials, maintenance products and practices, and operating strategies that provide acceptable indoor air quality (IAQ) to building occupants. In many discussions of green buildings, there is an implication that an exceptionally good indoor environment is being provided, but the specific characteristics of the air that make it exceptional are typically not stated. In fact, while a general consensus may exist on some aspects of good indoor air quality practice (EPA 1991; Levin 1991), much remains to be done in defining the details of "good" indoor air quality. However, there is a general consensus on what constitutes good practice. The major shortcomings in specifying good indoor air quality are the lack of standardized measurement techniques for the concentrations of most pollutants and for pollutant emission rates, the myriad of contaminants that can exist within the built environment, and the need for more information on the health effects related to these contaminants.

Discussions of green buildings include presentations of green building demonstration projects, in which the principles of green building design are featured in a particular building, and green building rating schemes, which are presented as a means of establishing the "greenness" of a building. This paper reviews the indoor air quality principles presented in both green building demonstration projects and green building rating systems. Before that, some general principles on design, operation, and maintenance practices for achieving good indoor air quality are presented. The manner in which the discussions of green buildings deal with indoor air quality is then compared to these principles. To assess the indoor air quality performance of a green building and to demonstrate methods aimed at verifying indoor air quality performance, a case study of green building performance measurements is presented. This case study includes a description of the building, its "green" indoor air quality design features, a description of the measurements performed, and the results of these measurements.

ISSUES RELATED TO INDOOR AIR QUALITY

The idea of providing good indoor air quality in buildings does not pertain exclusively to green buildings. This section presents a brief review of the major issues related to building

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indoor air quality design and performance based on a discussion of building design issues related to indoor air quality presented by Levin (1991).

Ventilation and Climate Control

Ventilation and climate control refers to the provision of clean outdoor air and properly conditioned supply air to the occupiable spaces of a building. Outdoor air is provided as a means for diluting occupant-generated bioeffluents and other indoor contaminants, and conditioned air is provided to maintain occupant comfort throughout a building.

Outdoor Air Intake Outdoor air can be provided to the building either mechanically or via openable windows or vents. When mechanical ventilation is to be provided, relevant standards are typically referenced to determine design intake rates, e.g., *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989). Outdoor air intakes should be located to avoid known outdoor pollutant sources such as vehicular emissions and other building exhausts. Strategies for providing special ventilation during construction and early occupancy are sometimes suggested. This can include a building flush-out period in which high ventilation rates are employed to dilute high contaminant levels that may exist due to construction activity and new materials.

Filtration and Air Cleaning The issues of particle filtration and cleaning of gaseous contaminants in ventilation air involves both the type of filtration or cleaning as well as the scheduled inspection and replacement of the systems.

Humidification Humidification issues are geared toward both preventing excessive indoor humidity levels, to minimize the potential for microbial contamination and providing thermal comfort to building occupants. If humidification is required, the use of steam-based systems is being encouraged, as opposed to cold water spray systems, in order to minimize the potential for microbial contamination.

Thermal Comfort Thermal comfort addresses the performance of the ventilation system with respect to maintaining the comfort of the building occupants. Thermal comfort is a function of air temperature, relative humidity, radiant temperature, air speed, and other occupant-related factors (metabolic rate, clothing, etc.). Standards exist upon which the ventilation system should be designed to achieve acceptable thermal comfort conditions (ASHRAE 1992; ISO 1984).

Pollutant Source Control

There are several aspects of source control that are related to building design and operation. These include the careful selection of materials that will go into a building based on chemical characteristics, the exclusion or isolation of potentially harmful pollutant-generating activities, and properly designing, constructing, and maintaining building systems and components to prevent microbial contamination and excessive buildup of pollutants.

Material Selection This issue of careful selection of building materials, furnishings, and maintenance products is important to establishing an acceptable indoor environment. It is suggested that building materials should be selected based on chemical composition and low chemical emission characteristics. This could be as simple as referencing material safety data sheets (MSDS) if they exist for a product or performing tests on potential products to establish emission characteristics (ASTM 1990). This was a major focus of an indoor air quality program developed for some new office buildings in the state of Washington (Black et al. 1991). In this program, material emission guidelines were developed for total volatile organic compounds (TVOC) and formaldehyde. Materials that were given attention included those that have a high loading (e.g., floor coverings, paints, and office furniture) and those that typically contain volatile compounds (e.g., finishes and adhesives). It is suggested that only those materials that do not contain urea formaldehyde as well as those that exhibit "low" TVOC emission characteristics should be used in buildings.

While it is certainly desirable to employ low-emitting materials in buildings (Levin 1996a), a number of issues make the implementation of this intention difficult. Attempts to specify and employ low-emitting materials are made difficult due to the lack of consensus standards on how to measure emissions and, similarly, the lack of health-based emissions guidelines. While a guideline to chamber testing of emission rates exists (ASTM 1990), there are no standard test methods for determining emission characteristics either within a chamber or as installed within a building. In fact, various test methods are currently being used to measure emission rates, and these methods can yield different results. This variability was revealed in an interlaboratory comparison of small chamber measurements of a known and common source (De Bortoli and Colombo 1993), as well as in a comparison of different TVOC sampling techniques by Hodgson (1995). In the State of Washington study, TVOC emission characteristics of materials were determined within a test chamber, and results were used in a predictive exposure model to determine concentrations under annualized building ventilation conditions. As was done in the case study presented in this paper, measurements of TVOC concentrations in a building can be coupled with measured outdoor air intake rates to determine TVOC emission rates in a building. However, these methods are based on many assumptions whose validity has not been well established, and research is needed into their use (Persily 1996). Also, additional research is needed on the health effects associated with TVOC exposure levels before health-based guidance can be developed (Mølhave and Clausen 1996).

Smoking and Source Isolation Pollutant-generating activities need to be considered in the overall design of a building, including photocopying, food preparation, and graphic arts. An attempt should be made to locate the spaces containing these activities such that emissions will have a minimum impact on occupiable areas of the building. Ventilation systems for these spaces should be designed and operated to prevent emissions from being transported to other parts of the building.

This can be done by providing dedicated exhaust systems and not allowing recirculation of the air from these spaces into the ventilation system. Care also should be taken to prevent the transport of pollutants from areas in which construction activities are taking place into occupied portions of the building.

Some indoor air quality guidance documents recommend either a no-smoking policy or that isolated smoking areas be provided within a building (EPA 1991; BEPAC 1993; BRE 1993a, 1993b; Hayward et al. 1994). If smoking is allowed, the recommendations suggest that smoking lounges should be provided that are isolated from the rest of the building by providing a one-pass ventilation system with no recirculation, and these lounges should be negatively pressurized relative to the surrounding space.

Microbial Control Ventilation systems should be designed to prevent moisture buildup. This includes the prevention of condensation within ducts, the prevention of moisture buildup in duct liners, and the provision of positive drainage of cooling coil drip pans to prevent the occurrence of standing water within the system. It is typically recommended that no humidification system be provided, but if one is, it should be of a steam-based type as opposed to the commonly used spray-based type.

Radon During the design phase of construction, soil should be tested for its potential as a radon source. If warranted, mitigation measures can be incorporated into the building design.

Building Performance

While the design issues discussed above are fairly comprehensive in addressing indoor air quality, the actual impact of their consideration at the design stage can only be determined through testing of the constructed and occupied building. However, no standard approaches exist for such performance evaluation. While building commissioning is beginning to gain acceptance as a method for verifying building performance, it is generally focused exclusively on heating, ventilating, and air-conditioning (HVAC) system performance. According to *ASHRAE Guideline 1* (ASHRAE 1996), commissioning begins early in the design phase of construction with the documentation of design features, including those related to indoor air quality (e.g., design assumptions, design ventilation rates, humidification system specifications, etc.). Commissioning is complete once proper operation of all systems has been verified by testing and comparison to design specifications. This includes the testing, adjusting, and balancing of the ventilation system airflows. However, building commissioning is geared toward verifying HVAC system performance with respect to system specifications, and it does not typically address indoor air quality and other building performance issues, with the possible exception of some thermal comfort parameters. However, indoor air quality commissioning procedures have been proposed and implemented (Dols et al. 1995; Sterling et al. 1992). These procedures are geared toward the direct measurement of various indoor environmental parameters, but they have yet to gain wide acceptance and use.

INDOOR AIR QUALITY IN GREEN BUILDINGS

This section presents a review of how indoor air quality issues are addressed in both green building demonstration projects and green building rating systems. The aforementioned discussion of indoor air quality is used as a basis on which the projects and rating systems are compared.

Demonstration Projects

A review of the proceedings of the 1994 and 1995 Green Building Conferences (Fanney et al. 1994, 1995) was performed to identify green building demonstration projects. Of about a dozen projects that were presented in the proceedings, about half of them mention indoor air quality as a consideration in the project, and of those, only a few give specific information regarding the consideration given to indoor air quality. Most projects in which indoor air quality is mentioned as a consideration tend only to make the qualitative statement that "good" indoor air quality will be a feature of the demonstration building(s). Typically, no quantifiable information is given as to how this air quality will be achieved or verified. Also, there is little consistency among the projects as to the general and specific considerations given to achieving good indoor air quality.

There are some common issues among those projects that did mention indoor air quality, the provision of outdoor air ventilation and the use of materials with low VOC emission characteristics. However, several issues were not typically covered, for example, other pollutants, thermal comfort, and ambient air quality. A couple of the projects mention specific issues that were addressed related to indoor air quality. The most comprehensive of these demonstration projects was the Audubon House renovation project in New York City. This project provided detailed information on the design of the ventilation system and the selection of building materials to avoid the introduction of VOCs and formaldehyde into the building. Details of this project are presented as part of the case study later in this paper. One other project mentioned specific design requirements related to ventilation rates and maximum acceptable formaldehyde levels, which were verified by measurement (Loken 1995).

Green Building Rating Systems

In an attempt to begin quantifying the "greenness" of "green buildings," rating systems are being developed. There are several green building rating systems either in existence or under development (BRE 1993a, 1993b; BEPAC 1993; USGBC 1996). The issues addressed within these rating systems are often categorized according to the type of building, whether the building is new or existing, and whether they pertain to building materials and services or building operation and management.

There is a clear consensus within the "green building" community that the provision of good indoor air quality is an important feature of green buildings. Both the existing and the proposed systems address the issue of indoor air quality to varying degrees and levels of detail. One of the predominant features of these rating systems is that they tend to emphasize design and proposed management practices as opposed to verified building performance with respect to indoor air quality. Of course, this emphasis on good design is a reasonable starting point in achieving good indoor air quality by implementing building practices that have the potential for improving the indoor environment, but it is also critical to verify the proper implementation of design and ultimately good operation and maintenance practices. This is not to say that verification is completely ignored in these rating systems, but a greater emphasis on actual performance may be helpful in realizing the intended "greenness" of the indoor environment in a building. Some rating systems present issues that are being considered for future inclusion. Among these is the provision of a permanent environmental monitoring system.

The ranges of indoor air quality issues addressed by the current rating systems are fairly comprehensive when compared to those presented previously in the discussion of indoor air quality. The issues covered typically fall into the categories of ventilation, pollutant source control, and operation and management practices. It is mostly in the level of detail and the referenced documentation that these systems differ. Typically, these systems refer to other guidelines, standards, and documentation for details on implementing features of the systems. However, the references for contaminant limits sometimes are criteria developed for the ambient environment as opposed to the indoor environment.

The discussions of good indoor air quality design that were presented earlier were not necessarily developed based on the consideration of the global environmental issues associated with the concept of green buildings. Even the indoor air quality design issues presented in the various rating systems may or may not conflict with other elements of green design such as reduced energy consumption. Therefore, green building features aimed at providing good indoor air quality must be balanced with building features that are geared toward having a minimal negative impact on the global environment. For example, increased outdoor air intake should be balanced with the energy required to condition the air. Also, when selecting low-emitting materials, consideration should be given to other characteristics of the material, such as the manufacturing process, transportation to the building site, and disposal of the product (i.e., cradle-to-grave characteristics). Thus far the methodologies that will enable the evaluation of building materials with respect to environmental and economic performance, referred to as life-cycle assessment and life-cycle cost, are not implemented in the current rating systems (Lippiatt and Norris 1995).

CASE STUDY

A test protocol was established and used to measure several indoor air quality-related parameters in a newly renovated green office building. The test protocol and parameters measured were similar to those employed in an indoor air quality commissioning program developed for and applied to a new office building (Dols et al. 1995). This protocol is not intended to implement the most sophisticated techniques for indoor air quality measurement and analysis, but rather to provide information that is relevant to the major indoor air quality issues presented in the previous sections and to do so with a reasonable amount of effort. Measurements were made while the building was occupied and under normal operating conditions over two consecutive workdays in November 1995. Measurements were made in three categories of parameters: ventilation, pollutants, and thermal comfort, as listed below.

Ventilation Performance	Pollutants	Thermal Comfort
Outdoor airflow rate	Carbon dioxide	Temperature
Pressure relationship between zones	Carbon monoxide	Relative humidity
	Formaldehyde	Percent predicted dissatisfied
	Particulates	
	Volatile organic compounds	

Building Description

The building consists of nine floors above grade (floors one through nine) and two basement levels. The basement levels contain equipment rooms and storage areas, and the remaining floors are made up of office and retail space. Floors one through three are leased for retail and office space. The building owners occupy floors four through nine, which is all office space; however, the ninth floor consists only of a conference facility (which is significantly smaller than the occupiable space of the other floors) and a mechanical equipment room. The occupiable area of floors four through eight is approximately 690 m^2 (7,400 ft^2) each. The mechanical equipment room located on the ninth floor houses the major mechanical systems including the main outdoor air intake fan that provides outdoor air to all the lower floors of the building through a single vertical shaft. There is a mechanical room located on each floor of the building on levels one through nine, into which the vertical outdoor air shaft delivers outdoor air through a damper. Supply air handlers are located within the mechanical rooms of each floor to provide conditioned air to the floor. Outdoor air and return air mix within the mechanical rooms to make up the supply air delivered to the occupied space.

Green Building Features

This building was designed with the intention of providing good indoor air quality and a comfortable working environment for the occupants through the consideration of architectural features, material selection, and ventilation system design (NAS

1994). Architectural features included for the purpose of improving indoor air quality were the incorporation of openable windows and the placement of the outdoor air intake away from obvious pollutant sources. Openable windows were included as a means of providing local comfort and ventilation control to the building occupants. However, the air quality impacts of openable windows are not clear, as the direction and rate of airflow is not controlled, and any air that does enter the building is not filtered or conditioned. Also, use of these windows can lead to increased energy consumption when the space-conditioning systems are operating. The outdoor air intake was located on the roof of the building away from the exhaust vents and the street level, where heavy vehicular traffic occurs.

Material selection was made with close attention being paid to the existence of toxic components in products. This was done by reviewing material safety data sheets and lists of composition of potential products. An attempt was made to avoid formaldehyde-containing products by substituting a recycled paper product for plywood subflooring and avoiding pressed-wood products when selecting office furniture. Other attempts to utilize materials with low chemical emissions included the installation of wool carpet and jute padding and the use of paints that did not off-gas volatile organic compounds (VOCs) and that had a chemical composition considered acceptable by the design team. The use of adhesives was also avoided whenever possible.

Several aspects of the ventilation system design were geared toward providing good indoor air quality. The outdoor air is filtered using high-efficiency bag filters (85% dust spot efficiency), and the intake vent was located under a large overhang to minimize moisture intake. Also, the ventilation system was designed to bring in significantly more outdoor air than the 10 L/s (20 cfm) per person recommendation for office space in ASHRAE Standard 62. The design indicates a minimum design outdoor air intake rate of approximately 12.3 L/s per person (26 cfm/person) (NAS 1994). In reviewing the building mechanical plans, the design outdoor air intake rate is given as approximately 540 L/s (1,150 cfm) per floor. The space-use plans showing office furniture layout indicate an occupant density between 27 and 35 persons per floor under normal occupancy conditions, which translates to an outdoor air intake rate between 15.4 L/s (33 cfm) per person and 20 L/s (43 cfm) per person. While it is unclear what the actual design outdoor intake rate is for this building, it appears to be well above the recommendation of the ASHRAE standard. Although increased outdoor air intake can be beneficial from an indoor air quality perspective, it increases energy consumption and the environmental impacts associated with providing this energy.

Measurement Techniques

This section briefly describes the techniques used to the measurements, which were performed in the building on November 29 and 30, 1995. During these two days, an automated carbon monoxide and carbon dioxide monitoring system was operating continuously, and several other air-sampling instruments were used to perform spot sampling throughout the day. Spot samples were taken in at least two locations on each floor, and some floors were monitored in up to six different locations for each round of testing. A round of spot measurements was performed twice each day, once in the morning and once in the afternoon. Some locations were monitored even more frequently during the second day in order to reveal temporal variations that may exist over the course of a day. Measurements were performed only on floors four through nine in addition to the outdoors.

Outdoor Airflow Rate Outdoor airflow rates to each zone were measured by performing a velocity traverse of the outdoor air delivery duct serving each zone with a hot-wire anemometer. The average velocity was then multiplied by the cross-sectional area of the duct at the traverse location to obtain the airflow rate. Ventilation rates were used to determine per person outdoor air intake rates as well as to calculate pollutant source strengths.

Pressure Relationships Between Zones Pressure relationships between zones were evaluated using smoke tubes to establish the direction of airflow between zones. Tests were performed to establish the relationships between the occupied spaces of all floors of the building and the stair, elevator, recycling shafts, and restrooms. On the lower three floors of the building, some of the spaces were inaccessible to the measurement team; however, the major pathways to and from the shafts were generally accessible.

Carbon Dioxide and Carbon Monoxide Carbon dioxide and carbon monoxide concentrations were measured using both an automated system and portable monitors. The automated system operated continuously for the two days of sampling. Automated sampling locations included the return airstreams of floors four through eight; the supply airstreams of floors four, six, and eight; and the outdoor air at the roof of the building. Each location was monitored once every 20 minutes. Portable monitors were used to take samples throughout the occupied space of each zone and from the outdoor air.

Formaldehyde Formaldehyde levels were measured on both days using passive samplers that determine an average concentration over a period of about eight hours, beginning around 9 a.m. each morning. Samples were taken in at least two locations in the open office space of each zone as well as at the main outdoor air intake.

Particulates Particulate sampling was performed using a respirable aerosol mass monitor based on a piezoelectric balance, which collects particulates from 0.01 μm to 10 μm in diameter. Short-term samples (five minutes) were collected throughout the open office space using this device.

Volatile Organic Compounds Measurements of volatile organic compounds (VOCs) were performed on both days of sampling. On both the first and second days, one set of samples was collected on floors four, five, seven, and eight. On the first day the sixth floor was sampled twice, once in the morning and once in the afternoon, and two outdoor samples were taken, one before and one after the indoor measurements. On the second day, the sixth floor was sampled seven times throughout the day, and the outdoors was sampled five times. This measurement strategy was employed to characterize the spatial and temporal variation of VOCs within the building as best as could be accomplished given the number of locations to be monitored and the rate at which samples could be collected.

All indoor VOC samples were taken at the return air duct just inside the mechanical room of each floor, and the outdoor samples were taken just outside the outdoor air intake grille. Samples were collected using a portable pump to draw air from the sample location through a tube (trap) filled with sorbent (0.5 g of 35/60 mesh of 2,6-diphenyloxide). Two samples were collected at each sample location, with one- and two-liter sample volumes. The samples were then analyzed with a gas chromatograph connected to a mass spectrometer (GCMS) with a mass selective detector (MSD). The concentration of total volatile organic compounds (TVOC) was determined by combining the responses of all organic compounds found in the sample having retention times between those of methylene chloride and n-tetradecane. The combined response was then compared to the response to an internal deuterated toluene standard to determine the TVOC concentration in $\mu g/m^3$.

These concentrations were then used with the measured outdoor airflow rates to estimate source strengths. These estimates employed the simplifying assumptions that the indoor TVOC concentration was at equilibrium and there were no VOC sinks in the building using the following equation (Persily 1996):

$$S = (C_{in} - C_{out}) \cdot Q_{oa}/A \qquad (1)$$

where

S = source strength per unit floor area, $mg/m^2 \cdot h$;
C_{in} = indoor TVOC concentration, mg/m^3;
C_{oa} = outdoor TVOC concentration, mg/m^3;
Q_{oa} = outdoor airflow rate into zone, m^3/h; and
A = floor area of zone, m^2.

Thermal Comfort Temperature and relative humidity were measured using an electronic hand-held sensor, and the predicted percent dissatisfied (PPD) was measured using a thermal comfort meter. PPD measurements were performed assuming a clothing value of 0.16 $m^2 \cdot °C/W$ (1.0 clo) for typical indoor winter clothing, a metabolic rate of 81 W/m^2 (1.4 met), and a vapor pressure of 0.3 kPa.

Measurement Results and Discussion

This section presents the results of the two days of measurements. Combined standard uncertainties of these results are presented, and the methods used to determine these uncertainties can be found in Dols et al. (1995).

Outdoor Airflow Rate The results of the outdoor air intake rate measurements for each zone of the building are presented in Table 1. In most cases the outdoor air intake rate to each zone was less than the design outdoor air intake rate of roughly 540 L/s (1,150 cfm) with the exception of the seventh floor, which was slightly greater than the design value. It is important to note that these measured values reflect only the operating conditions at the time of the measurements and may not necessarily indicate conditions at other times.

The measured outdoor air intake rates were used to calculate the per person outdoor air intake rates that are also presented in Table 1. The combined standard uncertainty of the measured airflow rates is approximately 4% of the reported values. Occupancy levels for these calculations were obtained by counting the number of occupants in each zone during each set of measurements and averaging them for both days of measurements. As previously stated, the outdoor air intake system was designed to provide more than the recommendation in ASHRAE Standard 62 for office space of 10 L/s per person, somewhere between 12.3 and 20 L/s per person, depending on

TABLE 1
Outdoor Air Intake Measurements

Location	Date	Time	Average Occupancy	Outdoor Air Intake Rate L/s	Outdoor Air Intake Rate L/s per peson
4th floor	11/29/95	12:00	14	140	10
		16:00		130	9
	11/30/95	11:00		140	10
		16:00		150	11
5th floor	11/29/96	15:00	17	330	20
	11/3095	11:00		240	15
		15:30		320	19
6th floor	11/29/95	10:00	24	140	6
		17:00		170	7
	11/30/95	9:00		170	7
		14:00		140	6
		16:00		150	6
		17:00		140	6
		20:00		160	7
		21:00		150	6
7th floor	11/29/95	14:00	24	600	25
	11/30/95	10:00		650	27
		15:00		570	24
8th floor	11/29/95	11:00	17	340	20
		16:00		310	18
	11/30/95	10:00		490	29
		15:00		370	22

how it is estimated. Based on these measurements and occupant counts, the recommended ventilation rates given by ASHRAE were met in all zones except the sixth floor. It is also important to note that meeting the ventilation rate requirements in the design or in ASHRAE Standard 62 does not necessarily guarantee that there are no air quality problems in the building. Conversely, if the actual ventilation rates are below these requirements, it does not mean that an unhealthy or uncomfortable indoor environment will definitely exist in the building.

Pressure Relationships Between Zones The results of the smoke tests are summarized in Figure 1. This figure is a schematic of the major zones of the building and does not depict all of the flow paths and interconnections of the major zones of the building. The dark arrows indicate the dominant direction of airflow. The white arrows indicate a less frequently encountered direction of airflow for those paths through which the direction of airflow varied between measurements. The spiral staircase is partitioned from the occupied space on the fourth and seventh floors and is open to the occupied space on floors five and six.

On the lower floors of the building, air tended to flow from the occupied space into the stair and main elevator shaft and in the opposite direction on the upper floors. The opposite was occurring with respect to the freight elevator shaft. The height at which the change in direction of airflow occurred varied between the different shafts of the building but tended to occur

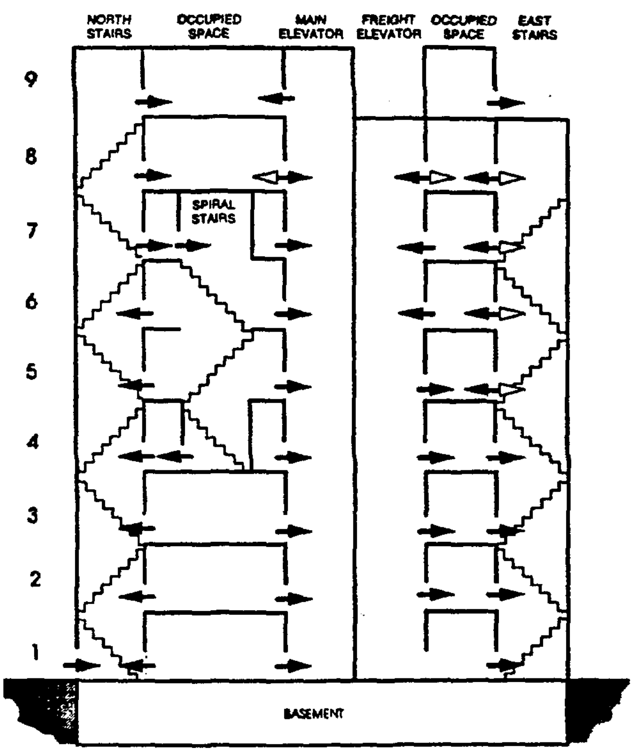

Figure 1 Summary of pressure relationships between zones (smoke test).

between the fifth and seventh floors. Also, air flowed into the building at the main entrance and out of the building through an exit onto a terrace located on the ninth floor of the building. The restrooms were negatively pressurized relative to the occupied space, and air tended to flow into the space from the recycling shaft on floors four through seven and from the space into the recycling shaft on the eighth floor. There are no specific requirements related to relative pressurization other than bathrooms, which should be negatively pressurized relative to the occupied space.

Carbon Dioxide The results of the automated carbon dioxide measurements are shown in Figure 2. The results obtained using the portable monitor were similar to the automated results. The sixth floor is shown separately because it revealed the highest measured concentrations (approximately 900 ppm) during the afternoon on both days of measurements. These relatively high levels found on the sixth floor correspond to the lower per person ventilation rates that were measured. The average carbon dioxide level for the other floors peaked at about 700 ppm on both days.

The uncertainty associated with the carbon dioxide measurements is based on calibrations of the CO_2 monitor using calibration gases. Based on the 95% confidence interval estimate for these calibrations, the uncertainty of the measured concentrations was about ±20 ppm for concentrations between 350 ppm and 1,000 ppm.

Carbon Monoxide Carbon monoxide was also monitored continuously using the automated system, and the indoor and outdoor concentrations remained less than 2 ppm over the entire two-day measurement period. The uncertainty associated with the carbon monoxide measurements is based on calibrations of the CO monitor using calibration gases. Based on the 95% confidence interval estimate for these calibrations, the uncertainty of the measured concentrations was about ±3 ppm.

Formaldehyde The results of the formaldehyde measurements are shown in Table 2. All of the eight-hour measured formaldehyde concentrations were less than 15 ppb. These concentrations are well below the level of 50 ppb that is considered to be of limited or no concern by the World Health Organization (ASHRAE 1989). These relatively low measurements are probably due to the efforts made by designers to limit the use of formaldehyde-containing products in the building. The uncertainty in the formaldehyde samples was estimated based on the analysis of duplicate measurements (samples taken in the same location at the same time). By pooling together all of the duplicate samples, a 95% confidence interval estimate was determined for all of the samples to be approximately ±2.4 ppb.

Particulates The results of the particulate measurements are shown in Table 3. The values presented in the table are for the morning and afternoon sets of measurement on each day of sampling. Each value is the average of between four and six measurements taken in each zone. The individually measured indoor particulate concentrations were all less than 50 $\mu g/m^3$,

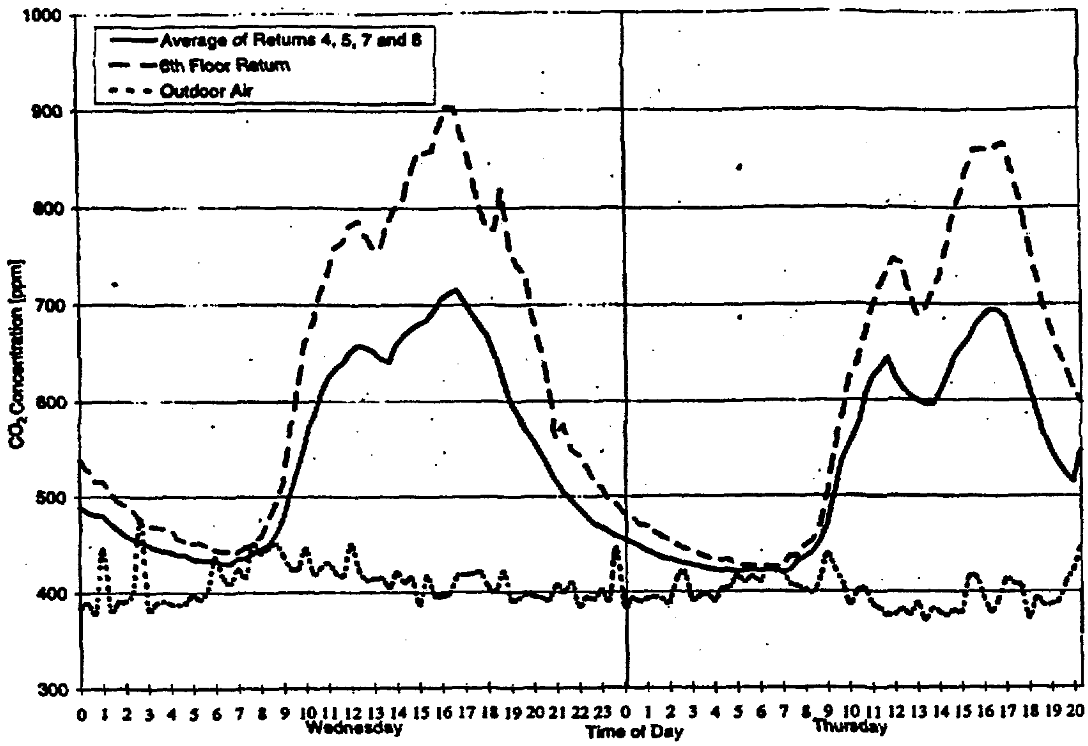

Figure 2 Automated CO_2 measurement data.

TABLE 2
Formaldehyde Measurements

Location	Formaldehyde Concentration [ppb]	
	11/29/95	11/30/95
4th floor	10	13
	10	10
	10	8
5th floor	13	12
	12	6
6th floor	13	10
	14	11
7th floor	10	9
	9	8
8th floor	12	9
	9	7
9th floor	8	7
	7	7
Outdoor Air	3	5
	3	3

TABLE 3
Particulate Measurements

Location	Time	Particulate Concentration			
		11/29/95		11/30/95	
		Average	Std. Dev.	Average	Std. Dev.
4th floor	Morning	15	4	6	3
	Afternoon	6	3	9	8
5th floor	Morning	15	3	12	3
	Afternoon	8	8	11	8
6th floor	Morning	13	6	13	5
	Afternoon	5	3	7	5
7th floor	Morning	10	10	18	16
	Afternoon	9	2	10	6
8th floor	Morning	9	1	10	6
	Afternoon	9	5	7	5
Outdoor Air	Morning	25	14	38	4
	Afternoon	24	15	12	14

and most were less than 25 μg/m^3. The maximum measured indoor and outdoor values were both approximately 40 μg/m^3. The mean indoor concentrations on an individual floor were all less than 20 μg/m^3. The uncertainty in these measurements is given by the manufacturer of the mass monitor to be ±10 μg/m^3 or 10% of the measured value, whichever is greater.

Volatile Organic Compounds The results of the VOC measurements are presented in Table 4 as total VOCs

TABLE 4
Total Volatile Organic Compound Measurements

Location	11/29/95				11/30/95			
	Time	TVOC Concentration [μg/m³]		Source Strength [mg/m²·h]	Time	TVOC Concentration [μg/m³]		Source Strength [mg/m²·h]
		Indoor	Outdoor			Indoor	Outdoor	
4th floor	14:00	210	80	0.10	12:00	230	100	0.22
5th floor	15:30	560	80	0.83	16:30	230	100	0.22
6th floor	11:00	490	80	0.30	8:00	280	60	0.19
	16:00	1790	80	1.54	11:00	190	60	0.12
					17:00	260	70	0.14
					15:00	270	70	0.15
					17:00	250	100	0.11
					19:00	290	100	0.16
					21:00	260	120	0.11
7th floor	15:00	310	80	0.73	14:00	230	70	0.45
8th floor	12:00	160	80	0.14	10:00	110	60	0.13

(TVOCs). The values reported are the averages of the two samples taken side by side at each location. The value presented for the outdoor air on the first day is the average of the two sets of measurements taken before and after the indoor samples were collected. The outdoor values for the second day are those that were measured closest in time to the corresponding indoor concentrations. The uncertainty in the TVOC samples was estimated based on the analysis of duplicate measurements. By pooling together all of the duplicate samples, a 95% confidence interval estimate was determined for all of the samples to be approximately ±20 μg/m³.

On the first day, TVOC concentrations were on average approximately 500 μg/m³ above the outdoor concentration and about 150 μg/m³ above outdoors on the second day. The standard deviations associated with these daily averages were approximately 120% and 30% of the average, respectively. There was a much wider variation in concentrations during the first day of measurements. Most notably, the afternoon sixth-floor sample was at least three times greater than all others. If this measurement were excluded from the analysis, the average indoor minus outdoor concentration would be approximately 270 μg/m³, which is still almost twice the average for the second day. It is not clear why the concentrations were higher on the first day than the second, but it would appear that there was a significant VOC source on or near the sixth floor.

Source strengths per unit of floor area were calculated based on the measured outdoor airflow rates using Equation 1. These values are also presented in Table 4 in units of mg/m²·h and are plotted in Figure 3. The uncertainty associated with the source strengths was determined to be between 5% and 10% of the reported values. This uncertainty was determined based on the propagation of uncertainty in performing the calculation using Equation 1. Figure 3 shows that the calculated source strengths were fairly constant between floors and over the course of the day for the second day of measurements. However, on the first day there appeared to be a significant source strength active in the afternoon that affected the measurements taken on floors five through seven. It is not clear what the source was that affected these measurements, but it appears to be related to three compounds that are much more prevalent in the samples taken on floors five through seven in the afternoon of the first day than they were in any of the other samples. The three compounds were 2-methylhexane, 3-methylhexane, and heptane.

There are several different methods currently in use for measuring TVOC concentrations, so it is difficult to compare results between different studies (Hodgson 1995). However, a recently performed indoor air quality commissioning study employed the same TVOC measurement method that was used in this study (Dols et al. 1995). The TVOC measurements in the commissioning study were performed during several stages of construction of a new building, including the early occupancy stage. When comparing the indoor minus outdoor TVOC concentrations between the early occupancy measurements of the commissioning study and those measured on the second day of this study, they are similar in magnitude, as are the source strengths. The average and standard deviations for the commissioning and this study are 157 ± 53 μg/m³ and 154 ±47 μg/m³, respectively. The respective average source strengths were 0.31 ± 0.07 mg/m²·h and 0.18 ± 0.10 mg/m²·h. These source strengths are less than 0.5 mg/m²·h, which is in the range of values reported for relatively "clean" buildings as indicated by Levin (1996b). Levin also reported that in most buildings in which both ventilation rates and TVOC concentra-

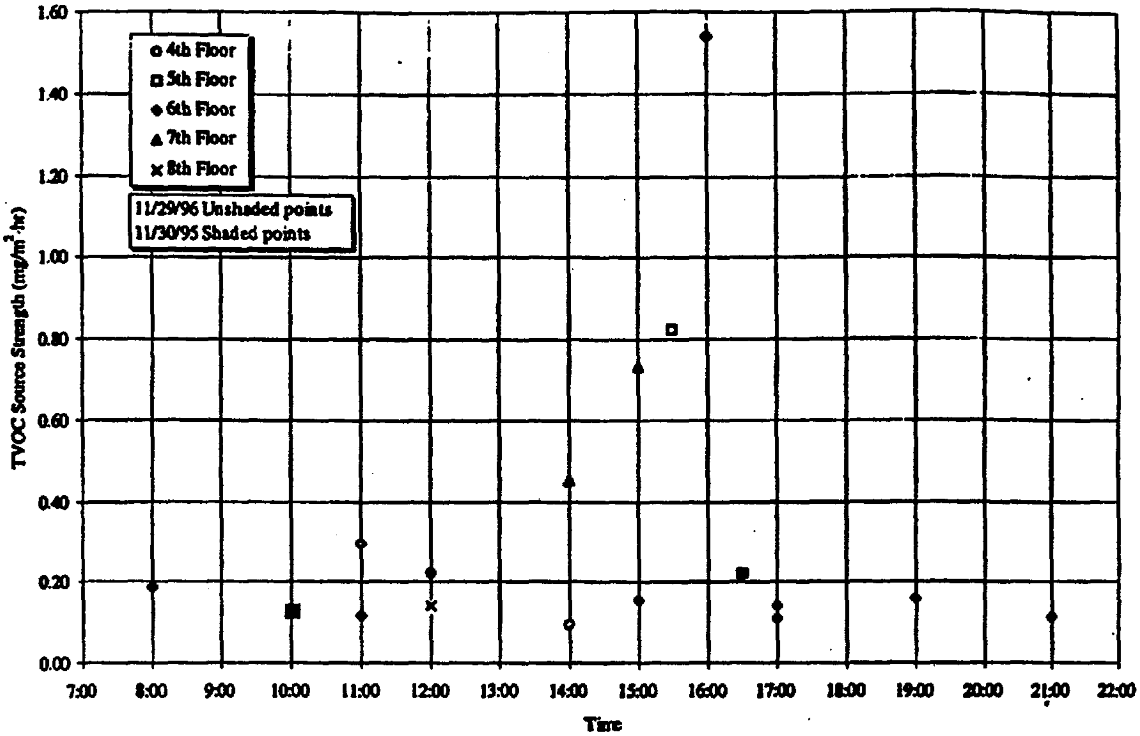

Figure 3 Plot of TVOC source strengths.

tions have been measured, building-wide average source strengths typically ranged between 0.5 mg/m^2·h and 1.5 mg/m^2·h, and in "less clean" buildings values have been measured between 2 and 10 mg/m^2·h.

Thermal Comfort Several environmental parameters were measured within the building to characterize thermal comfort. These measured parameters were temperature, relative humidity, and percent predicted dissatisfied (PPD). The results of the thermal comfort measurements are presented in Table 5 as the average measured values for a morning and ar afternoon set of measurements performed on each of the twi days of sampling. Each value shown in the table is the averagi of between two and six measurements taken throughout th entire zone. Temperature was fairly uniform throughout al zones, as indicated by the fact that standard deviations (no shown in the table) of each set of measurements were alway: within 5% of the average, and all measurements were betweei 21°C (70°F) and 25°C (77°F). The relative humidity wa:

TABLE 5
Thermal Comfort Measurements

Location	Time	11/29/96			11/30/96		
		Temp [°C]	%RH	PPD	Temp [°C]	%RH	PPD
4th floor	Morning	23	23	5	23	22	6
	Afternoon	22	26	5	23	20	6
5th floor	Morning	24	24	6	23	24	6
	Afternoon	24	27	5	22	21	6
6th floor	Morning	23	26	6	23	23	6
	Afternoon	24	26	6	23	21	6
7th floor	Morning	23	24	5	23	20	7
	Afternoon	23	23	5	23	18	6
8th floor	Morning	22	27	6	24	19	6
	Afternoon	24	22	6	23	21	6
Outside Air	Morning	8	50	—	3	46	—
	Afternoon	6	57	—	10	25	—

between 20% and 35%. All of the PPD measurements were below 10%, which is indicative of acceptable conditions for thermal comfort based on the assumptions of clothing and activity levels used in performing the measurements.

SUMMARY AND CONCLUSIONS

The manner in which indoor air quality is addressed in discussions of green buildings and green building rating systems was reviewed and discussed. In reviewing green building demonstration projects, it was seen that many issues related to indoor air quality were not discussed. The issues that were discussed, to varying degrees of specificity, were building ventilation and material selection for low VOC emissions. Also, indoor air quality issues were not always fully addressed with respect to their "greenness," e.g., the trade-off between increased ventilation and energy use. This is most likely due to the inherent difficulty in making these trade-off decisions between difficult-to-quantify parameters. Issues related to indoor air quality frequently were not mentioned at all, and only the energy-related issues were addressed. Based on the reviewed rating systems and demonstration projects, it appears that demonstration projects need to be more comprehensive and specific in addressing indoor air quality issues.

Indoor air quality guidance in general, including green building rating systems, is challenged by the current limits of knowledge and the inability to be quantitative on all issues, e.g., VOC concentration limits and emission guidelines. Specifically, there are no standard methods for determining emission characteristics of materials, and there are inadequate data concerning the health effects of the compounds emitted. This problem not only exists in the emission test laboratories but is further confounded by the unlimited possibilities of material combinations, loadings, and building operating conditions that can occur within the built environment.

Indoor air quality is an important feature in almost all discussions of green buildings and is featured prominently in current green building rating systems. However, these rating systems are focused primarily on building design as opposed to actual performance. As has been seen in many studies of building performance, design goals are not always realized in practice due to shortcomings in building construction, operation, and maintenance. Since there is no reason to expect that green buildings will not have similar problems, performance testing is key to determining whether indoor air quality design goals have been realized in green buildings. This was revealed with respect to several indoor air quality issues addressed in the case study of the green building demonstration project presented in this paper. TVOC measurements revealed an episode of elevated source strength significantly greater than those measured earlier the same day and the next day, indicating that even though much attention was given to the selection of building materials, unanticipated sources can still be introduced into the building. Elevated carbon dioxide levels appeared to be related to the outdoor air ventilation rates. Even though the building ventilation system was designed with ventilation rates well in excess of those recommended in ASHRAE Standard 62, the actual rates at the time of the measurements were below the design values on most of the floors. The reason for the discrepancy between the design and actual ventilation rates was not analyzed, but it is more likely to be an operational issue than a design issue. While differences between design and operation are not unusual in buildings, their existence points to the need for performance monitoring in green and other buildings.

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QUESTIONS AND COMMENTS

William S. Kerbel, Atlantic Environmental Inc., Dover, N.J.: What was the perception of occupants of the building with respect to the quality of the indoor environment?

Andrew K. Persily: While we didn't perform a survey of the occupants, we were told by building management that the occupants were generally pleased with the quality of the indoor environment.

Garvin Heath, U.S. EPA, Washington, D.C.: What determines "predicted percent dissatisfied"?

Persily: Predicted percent dissatisfied (PPD) is based on another thermal comfort index known as the predicted mean vote (PMV). PMV predicts the mean value of votes of a large group of people using a seven-point thermal sensation scale: -3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, and 3 = hot. PPD is determined empirically from PMV to predict the percentage of a large group of people that are likely to feel thermally uncomfortable, i.e., voting ±3 or ±2 on the PMV scale.

Based on a sampling of a large group of people, thermal comfort researchers developed an empirical relationship between several environmental parameters and the thermal sensation scale (ISO 7730). The PMV can be determined from this relationship by estimating the activity and clothing levels of an occupant and measuring these environmental parameters: air temperature, mean radiant temperature, relative air velocity, and partial water vapor pressure.

For the purpose of this project a thermal comfort meter was used that enables the direct measurement of PMV and PPD based on estimates of activity and clothing levels.